Chapter 13
Precambrian to Ground Surface Grid Cell Maps and 3D Model of the Anadarko Basin Province

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Volume Title Page

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Sean M. Strickland

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Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Anadarko Basin Province, Colorado, Kansas, Oklahoma, and Texas—USGS Province 58

Compiled by Debra K. Higley

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Introduction

The digital files listed in table 1 were compiled as part of the U.S. Geological Survey (USGS) 2010 assessment of the undiscovered oil and gas potential of the Anadarko Basin Province of western Oklahoma, western Kansas, northern Texas, and southeastern Colorado. This publication contains a three-dimensional (3D) geologic model that was constructed of two-dimensional (2D) structural surface grids across the province and Precambrian fault surfaces generated from Adler and others (1971). Also included are (1) 26 zmap-format structure grid files on Precambrian to present-day surfaces across the province; (2) estimated eroded thickness of strata following the Laramide orogeny and based on one-dimensional (1D) models and 1D extractions from the four-dimensional (4D) PetroMod® model (Schlumberger, 2011; Higley, 2014); (3) present-day weight percent total organic carbon (TOC) for the Woodford Shale based on TOC data from Burruss and Hatch (1989) and mean values from Hester and others (1990); and (4) basement heat flow contours (fig. 1) across the province based on data from Carter and others (1998), Blackwell and Richards (2004), and data downloads from the Southern Methodist University Web site (*http://smu.edu/geothermal/*).

The 3D geologic model and 2D grids were created using EarthVision® software [Dynamic Graphics Inc. (DGI), 2010] and grids were saved in zmap format. Lateral scales of the 3D model and all grids are in meters, and vertical scales of the structure and eroded thickness grids and model are in feet. TOC grid values are weight percent (wt %) and the heat flow grid is milliwatts per square meter (mW/m^2) (fig. 1). The age range represented by the stratigraphic intervals composing the grid files is 1,600 million years ago (Ma) to present day. File names and age ranges of deposition and erosion are listed in table 1. These time period assignments are generalized because of the lack of precise information regarding formation ages; there are no time overlaps because of modeling software requirements.

Metadata associated with this publication are within the AnadarkoMetadata.xml, AnadarkoMetadata.doc, and AnadarkoMetadata.htm files. Included are information on the study area and the names of the zmap-format grid files, such as file name and type, geographic coordinates of the grids and 3D model (table 2), and background information on the files in this publication.

Table 1. Two-dimensional grid file names, times intervals of deposition and erosion in millions of years ago (Ma), and lithofacies assignments.

[Grids represent the highest elevation of the named unit relative to sea level. Lithofacies that were assigned in the PetroMod® v. 11.3 software are included for archival purposes and names are not defined, merely labeled with general terms. Lithology names that are similar to layer names are custom lithofacies based on published distributions of facies or compositions that are mainly derived from sources that include Adler and others (1971), Denison and others (1984), Howery (1993), Ludvigson and others (2009), and the National Geologic Map Database (2011, *http://ngmdb.usgs.gov/Geolex/*)]

Number	Zmap file name	Deposition age		Erosion age		Total petroleum system assignment	Lithofacies value Assigned in PetroMod® (Part)
		from (Ma)	to (Ma)	from (Ma)	to (Ma)		
1	surfaceDEMft.DAT	1.83	1.8	1.8	0	Overburden rock	Sandstone (typical)
2	OgallalaTft.DAT	5.3	1.83	0	0	Overburden rock	Sandstone (clay poor)
3	CretaceousTft.DAT	250	33	33	5.3	Overburden rock	Sandstone (clay rich)
4	PermianTft.DAT	255	252	252	250	Overburden rock	Sandstone (subarkose, quartz rich)
5	BlaineTft.DAT	261	255	0	0	Seal rock	Blaine (custom lithologies)
6	StoneCorralTft.DAT	266	261	0	0	Seal rock	Limestone (shaly)
7	WellingtonTft.DAT	271	266	0	0	Seal rock	Wellington (custom lithologies)
8	ChaseTft.DAT	285	271	0	0	Reservoir rock	Limestone (shaly)
9	CouncilGroveTft.DAT	296	285	0	0	Reservoir rock	Limestone (shaly)
10	WabaunseeTft.DAT	298.2	296	0	0	Reservoir rock	Siltstone (organic lean)
11	HeebnerTTft.DAT	298.4	298.2	0	0	Seal rock	Shale (organic lean, typical)
12	HeebnerBTft.DAT	298.5	298.4	0	0	Seal rock	Siltstone (organic lean)
13	DouglasTft.DAT	304	298.5	0	0	Reservoir rock	Sandstone (typical)
14	DesmoinesianTft.DAT	305.3	304	0	0	Reservoir rock	Limestone (shaly)
15	CherokeeTft.DAT	308	305.3	0	0	Reservoir rock	Limestone (shaly)
16	AtokanTft.DAT	310	308	0	0	Reservoir rock	SHALEcarb
17	ThirteenFingerTft.DAT	311	310	0	0	Source rock	Limestone (shaly)
18	MorrowTft.DAT	324	311	0	0	Reservoir, seal rock	SHALEsilt, Sandstone (clay poor)
19	SpringerTft.DAT	354	330	330	324	Reservoir rock	Limestone (shaly)
20	WoodfordTft.DAT	369	354	0	0	Source rock	Woodford (custom lithologies)
21	HuntonTft.DAT	442	379	379	369	Reservoir rock	Limestone (shaly), Dolomite (typical)
22	SylvanTft.DAT	445	442	0	0	Seal rock	Shale (black)
23	ViolaTft.DAT	456	445	0	0	Reservoir rock	Limestone (organic rich - typical), Dolomite (typical), SHALEsilt
24	SimpsonTft.DAT	471	456	0	0	Reservoir, source rock	SHALEsilt, Sandstone (quartzite, very quartz rich)
25	ArbuckleTft.DAT	520	476	0	0	Reservoir rock	Limestone (organic rich - typical)
26	PrecambrianTft.DAT	1,600	544	544	520	Underburden rock	Granite (greater than 1,000 Ma old), Rhyolite
27	CreataceousErosionThickft.DAT		33	5.3			
28	HeatFlow_mWm2.DAT						
29	WoodfordTOC.DAT						

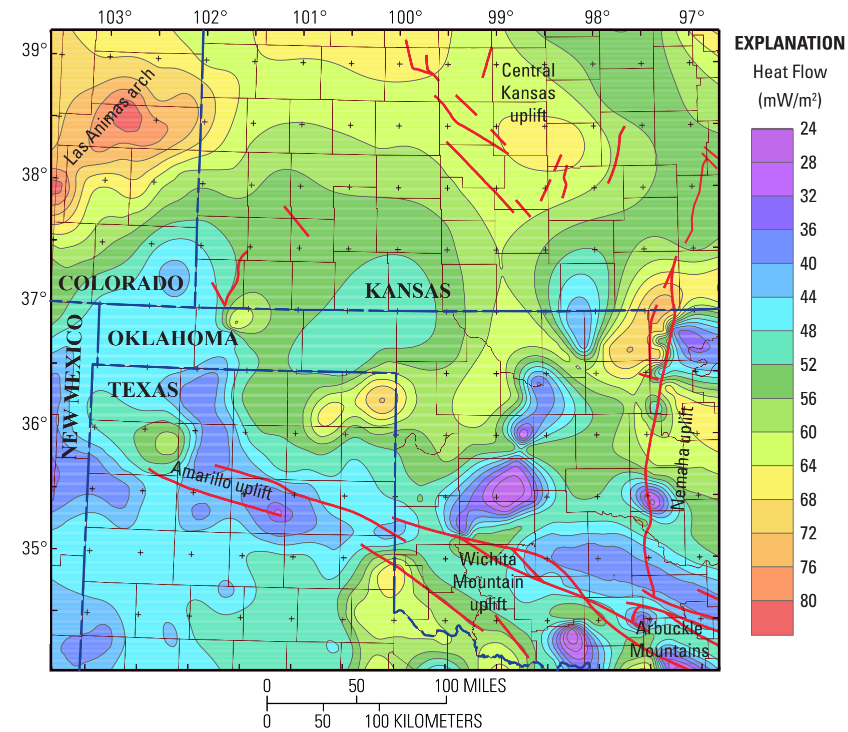

Figure 1. Geographic extent of grid files as displayed by basement heat flow contours across the Anadarko Basin Province based on data from Carter and others (1998), Blackwell and Richards (2004), and data downloads from the Southern Methodist University Web site (http://smu.edu/geothermal/). Basin areas north of the Wichita Mountain uplift and in the Amarillo uplift and northward exhibit generally lower heat flows than other basin areas. Highest measured heat flow is in the northwest, along the Las Animas uplift. The northwest-trending Central Kansas uplift (CKU) also exhibits elevated heat flow values. Heat flow units are milliwatts per square meter (mW/m^2). Precambrian faults (red lines) are from Adler and others (1971).

Table 2. Geographic coordinate information for the zmap-format two-dimensional grid files is located in the ZmapFormatGridFiles folder.

[All grid x and y dimensions are in meters and the grid spacings are 1 kilometer. Grid size refers to the total number of grid cells. Structure and erosional isopach grids z dimension is in feet relative to sea level. Contour values for total organic carbon (TOC) are weight percent carbon, and for basement heat flow are milliwatts per square meter (mW/m^2)]

Geographic coordinate system	Lambert Conformal Conic		
World Geodetic System (WGS)	WGS 84 ellipsoid		
First and second standard parallels (degrees, north)	35	38	
Central meridian (degrees, west)	99		
Latitude of origin (degrees, north)	35		
Semi-major axis, Semi-minor axis	6378137	6356752.3142	
False Northing, False easting	0	0	
X and Y dimensions of grid files			
Xminimum, Yminimum, grid cell size	–400000.0000	–100000.0000	601
Xmaximum, Ymaximum, grid cell size	200000.0000	475000.0000	576

Data Description and Processing Steps

1. Elevation, thickness, and fault data sources for the 2D grids and 3D model include formation tops from more than 220 wells across the province, edited formation tops from IHS Energy (2009a, 2009b) and the Kansas Geological Survey (2010, *http://www.kgs.ku.edu/PRS/petroDB.html*), and maps and data from Fay (1964), Adler and others (1971), Rascoe and Hyne (1987), Robbins and Keller (1992), Cederstrand and Becker (1998), Andrews (1999a, 1999b, 2001), and Rottmann (2000a, 2000b). Sources of ground elevations for 2D grids were well records and digital elevation model (DEM) data. Locations of formation outcrops/subcrops were derived primarily from surface geologic maps of the region and Rascoe and Hyne (1987). Formation ages and lithologies are commonly generalized; sources of information include Adler and others (1971), Denison and others (1984), Howery (1993), Ludvigson and others (2009), and the National Geologic Map Database (2011, *http://ngmdb.usgs.gov/Geolex/*).

2. Names and age ranges of formations change within and across the Anadarko Basin Province; consequently, data retrievals were based mainly on approximate age-equivalent units. Data files were edited using Environmental Systems Research Institute (ESRI) (2010) ArcMap™ and Dynamic Graphics, Inc. (2010) EarthVision® software to remove anomalies, examples of which include location errors and incorrect formation-top elevations. Maps generated with EarthVision® software were compared to published cross sections and maps, and anomalous surfaces were corrected by editing the scattered data files and regridding the files.

3. This chapter of the report contains fault trace and volume views of a standalone 3D geologic model of the study area. The model can be viewed and manipulated, and .jpg or .tiff images of user-defined views can be saved. Both a basic "getting started" and detailed help file were provided by Dynamic Graphics, Inc., and are in the 3Dviewer_HelpFiles folder as aids to understanding the included 3D viewer. The included 3D viewer is designed to work with the Microsoft Windows operating system. The USGS has licensed from Dynamic Graphics, Inc., the rights to provide an encrypted model that allows the viewers to use the enclosed data sets and interpreted model. The license allows the USGS the service and rights to provide unlimited distribution. We designed this product to function from the DVD–ROM media but recommend that the necessary files be copied to a local hard drive for better performance. No additional installation programs are needed to view the model and datasets using the 3D standalone viewer. Should there be error messages when starting the software that reference the Microsoft C++ libraries; selecting "OK" several times will start the software. The folder "bug fix" includes a possible fix for this error message problem and is provided as a courtesy by Dynamic Graphics, Inc. More information about the viewing software and EarthVision® may be obtained from Dynamic Graphics, Inc., at *http://www.dgi.com/*.

4. The extent and elevation of model layers in highly faulted and deformed areas is not well documented or constrained. For that reason, surfaces on and south of the Wichita Mountain and Amarillo uplifts should be considered erroneous. The modeling software requires all grids to extend to the map boundaries, even if the modeled strata are only present within a portion of the layer. The shallowest elevation of the immediately underlying surface is included for strata with limited geographic range. For example, the Woodford Shale is only located in the deep part of the Anadarko Basin of Texas and Oklahoma and in a portion east of the Central Kansas uplift (fig. 2), but the structure grid of this surface also includes Precambrian through Silurian "subcrops."

5. 2D grids downloadable from this publication and used to build the standalone 3D models were generated using the Dynamic Graphics, Inc. EarthVision® Briggs Biharmonic Spline algorithm. Horizontal scales are in meters. Coordinate information is provided in table 2, grid file headers, and the metadata files. The x and y grid spacing are both 1,000 meters. As many as 15 data values were evaluated from each grid node and a scattered data feedback algorithm follows each biharmonic iteration. These modeling steps result in the curvature of the surface being distributed between data points rather than concentrated at individual data points. This generates a more natural appearing modeled surface of the modeled grid nodes that accurately reflect the scattered data. Grids generated for this publication were not smoothed or filtered. More information on this process and software are available from Dynamic Graphics, Inc., at *http://www.dgi.com*. Volumes of units are defined and shown as the space between (1) two geologic surfaces, (2) geologic surfaces and fault planes, or (3) geologic surfaces and model extents.

   For the Earthvision® 3D model, faults were defined as extending from Precambrian basement to the ground surface. Due to modeling and time constraints, most intersecting faults were designated as vertical and thoroughgoing. Modeled faults were added sequentially as follows: (1) faults that cross the model, (2) faults that truncated other faults, and (3) faults to help show the basin geometry. Where data or details were missing, data points were extrapolated from known data points based on local thickness of modeled units or fault displacements. For example, if the only local data control for a surface was a contact on the geologic map, we used that X, Y, and Z value and calculated local overlying and (or) underlying z-surface-elevation values based on thickness. Some thickness and surface variations shown in the model may reflect additional small faulting or inherent uncertainties of defined picks from the data, but

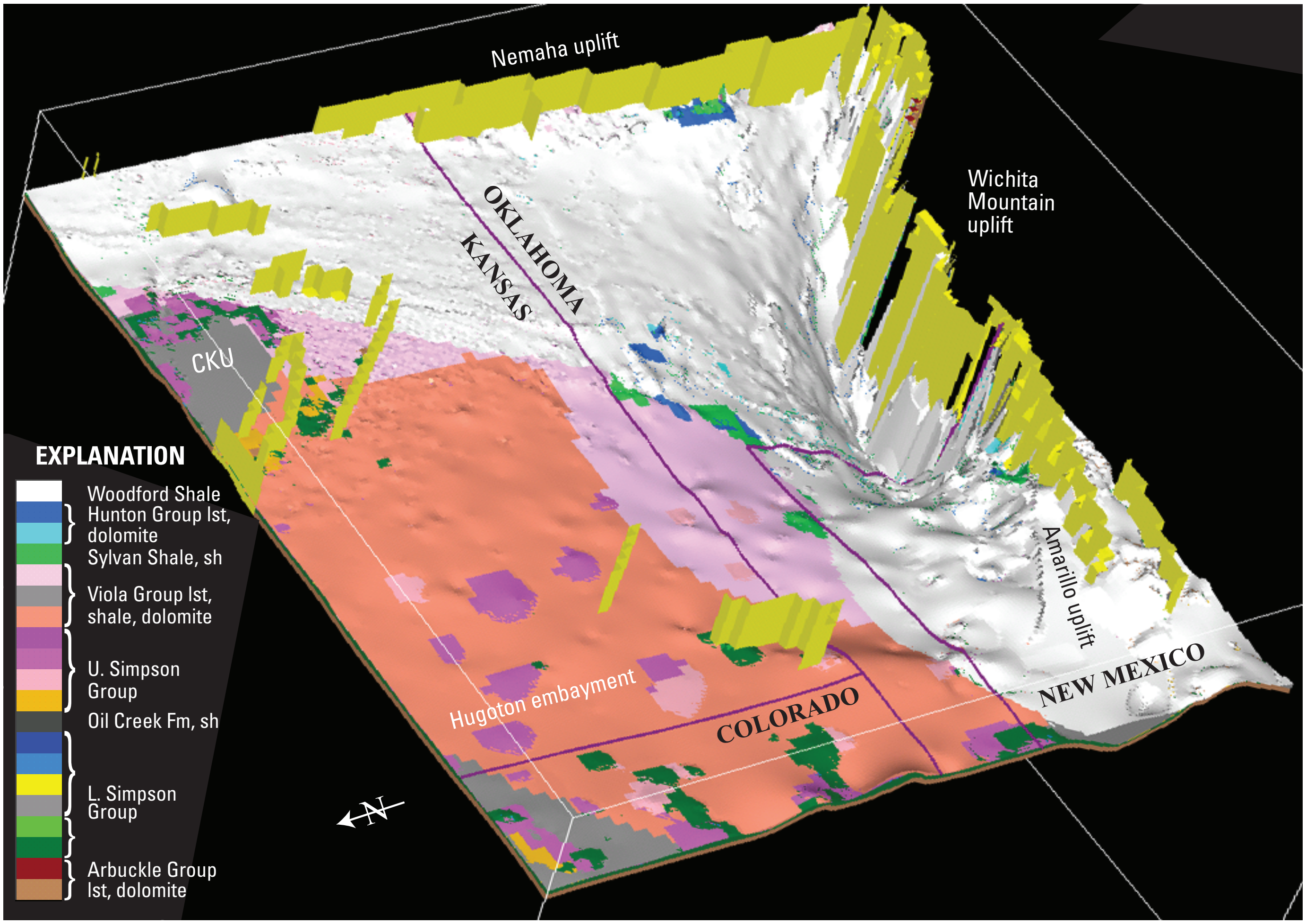

Figure 2. View to the southeast showing the Woodford Shale layer and modeled lithofacies. Vertical exaggeration is 18 times. Extent of the Woodford Shale is shown in white. This PetroMod® image shows underlying and lateral formations and facies changes for the Woodford Shale layer. The southern half of the Kansas portion has almost 0 meter thickness and represents grid extrapolation from the Woodford (Chattanooga) Shale east of the Central Kansas uplift (CKU) to the Woodford Shale proximal to the Kansas-Oklahoma border. Lateral lithofacies are primarily limestone and dolomite of the Viola Group. Because the purpose of this image is to show lateral changes in formation and lithofacies assignments on a model layer, this information is generalized in the legend and not all listed formations are visible. Vertical yellow bars are Precambrian faults from Adler and others (1971).

are considered to be reasonable interpretations based on objective criteria in surface maps, lithological descriptions, and geophysical interpretations.

The top of the Precambrian basement is the lowermost modeled unit and was used as a base for the deep fault structures in the 3D geologic model. This was necessary because the EarthVision® 3D modeling technique builds the geologic layers upward from the base, and fault displacement propagates vertically until other data are available or some model extent or boundary is reached. Geologic surface data were then edited proximal to the faults to generate clean fault scarps. This was necessary because converting grid files to X, Y, and Z data files commonly places data points on the fault scarps, which EarthVision® tries to interpret as geologic surfaces. This process and the associated 3D EarthVision® model were created subsequent to the PetroMod® zmap-format grid files in this publication, most of which have different terminations against the southern fault system. The PetroMod® 4D petroleum system model of the Anadarko Basin includes a modeled sequence of northward-stepping vertical faults along the Amarillo–Wichita Mountains uplift that are connected laterally at the tops and bases. Vertically curved faults are not an option with PetroMod®.

6. Negative isopach values can be present in grid files in areas where data are lacking, in which case negative thickness values were replaced by zero or 2 meter thickness because of requirements of the EarthVision® and PetroMod® modeling software. Identical structural surfaces

result in a mottled appearance in the EarthVison® 3D model because the software defines these intersections as a contact with a resulting black line. Grids were modified to exceed 1 foot in thickness in order to minimize identical surfaces. This process can result in the disappearance of units that are only a few feet thick.

Zmap-Format Grid Files

In table 1, names are listed for the 29 zmap-format grid files associated with this publication. Also included for archival purposes are PetroMod® model assignments of time periods of deposition and erosion, total petroleum system(s), and generalized lithofacies(s). Each PetroMod® structure grid contains at least one lithology but may have multiple assigned lithologies. These are represented by lateral changes in color within a model layer, such as is shown in figure 2.

Zmap-format grids include file headers with (1) a comment section with original file names and locations, file creation date and time; and (2) original file name and folder, file type, grid spacing, and coordinate information. The file structure is a series of rows and columns with values listed for each grid cell. Included data and coordinates are incorporated in maps and models by using software that reads zmap-format files. Software programs are available to import and convert zmap-format files. These grid formats can be read by EarthVision®, ArcMap®, and PetroMod®, as well as other mapping and modeling software. Metadata are saved in text (.txt) and XML (.xml) formats, the latter of which is readable using ESRI ArcGIS® and some XML, WWW, and word-processing software.

Standalone 3D Geologic Model Files

There are three standalone EarthVision® 3D geologic models, which are opened by double-clicking on the open_viewer.bat file located within the 3DgeologicModel folder and then selecting one of the three ".faces" files below. Background information on PC requirements, loading, opening, viewing, and manipulating the models is located within the Demo3DViewer.pdf and QuickHelp.pdf files located in the 3Dviewer_HelpFiles. Because the standalone model uses considerable processing power, the 3DgeologicModel folder should be moved to a computer hard drive before opening the model.

1. 5_3_11_hor.sliced.encn.faces—Model comprises the 26 structural surfaces listed in table 1. Also displayed are vertical red bands that depict the Precambrian faults of Adler and others (1971).

2. 5_3_11_hor.sliced.fault.encn.faces—Precambrian fault traces are treated as vertical faults, as opposed to incorporating the structural dips of these complex fault systems.

3. 5_3_11_hor.sliced.surf.encn.faces—Within this model, the Precambrian fault traces (gray) are vertical and extrapolated across the model to intersect other fault systems.

Computer Requirements to View the 3D EarthVision® Geologic Model

Windows® XP or Windows 7 Operating System Graphics Card Recommendations

- An OpenGL capable graphics card with dedicated memory is required.
- We recommend the graphics card have at least 512MB of memory onboard.
- Some large monitors (30-inch or greater) require a dual-link DVI capable connector.
- DGI recommends graphics cards from the NVIDIA Quadro FX series (NVIDIA Quadro FX with at least 512MB of memory) for use with its software.

Computer Processor Unit (CPU) Requirements

- Time to open, view, and manipulate a model is partially dependent on the processor speed of the PC CPU.
- Although most of DGI's software does not currently take advantage of multiple CPUs/Cores, their presence will allow running more software simultaneously without impacting performance.
- CPUs designed for lower power solutions (Ultra-Low Voltage [ULV] or Consumer Ultra-Low Voltage [CULV]) are not recommended at this time as they are optimized for decreased power consumption, rather than performance.

Memory Requirements

- 4GB memory minimum
- For 32-bit systems, 4GB is recommended. This is the maximum amount of memory supported on 32-bit Windows XP Professional system. However, depending on the BIOS (basic input output system) and operating system settings, the user may only see 3GB or 3.5GB available.

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This chapter of the report benefited from excellent technical reviews by Laura Biewick, Jennifer Eoff, and Gregory Gunther of the USGS. Gregory also generated the initial metadata associated with grid files in this chapter.

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